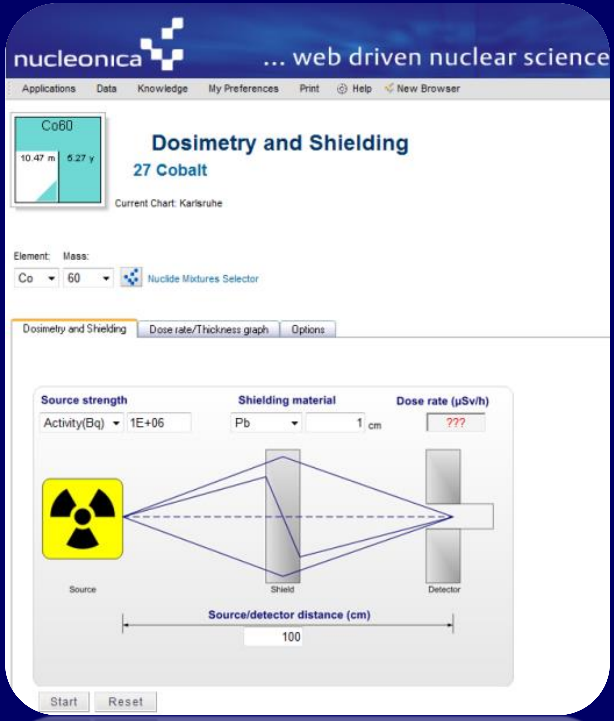
Gamma Dosimetry & Shielding

J. Magill



Overview…

Biological Effects of Ionising Radiation

- Absorbed dose, Quality or Weighting Factor, Equivalent Dose

Attenuation of Gamma Radiation

- Calculation of the energy absorption, calculation of the equivalent dose rate, absorption in tissue, attenuation in shield materials, build-up factors

Nucleonica´s Dosimetry & Shielding Module

Absorbed Dose

Usually the interaction of radiation with matter involves a transfer of energy from the radiation to the matter. Ultimately, the energy transferred either to tissue or to a radiation shield is dissipated as heat. The radiation dose depends on the intensity and energy of the radiation, the exposure time, the area exposed and the depth of energy deposition.

The modern SI unit of absorbed dose is the gray (Gy) where one gray is one joule per kilogram 1Gy = 1 J kg^{-1}. In dosimetry, it is useful to define an average dose for a tissue or organ D_T. The absorbed dose to the mass δm_T, is defined as the imparted energy δE_T per unit mass of the tissue or organ, i.e.

$$D_T = \delta E_T / \delta m_T.$$

The absorbed dose rate is the rate at which an absorbed dose is received. The units are Gy s^{-1}, mGy hr^{-1}, etc.

Biological effects depend not only on the total dose to the tissue but also on the rate at which this dose was received. In organisms, mechanisms exist which enable molecules such as deoxyribonucleic acid (DNA) to recover if they have not been too badly damaged. Hence it is possible for organs to recover from a potentially lethal dose provided that the dose was supplied at a sufficiently slow rate. This phenomena is exploited in cancer radiotherapy

Quality or Weighting Factor

The biological effect of radiation is not just directly proportional to the energy deposited by radiation in an organism. It depends, in addition, on the way in which the energy is deposited along the path of the radiation, and this in turn depends on the type of radiation and its energy.

Thus for the same absorbed dose, the biological effect from high LET radiation such as α particles or neutrons is much greater than that from low LET radiation such as β or γ rays.

The quality or weighting factor, w_R, is introduced to account for this difference in the biological effects of different types of radiation. The weighting factors for the various types of radiation and energies is given in the table.

Quality or weighting factors for different types of radiation

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy See Radiation weighting factors

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

[a] Note the special issue of Auger electrons discussed in ICRP 103 (2007).

$$H_{T,R} = w_R \cdot D_{T,R} \,,$$

where $H_{T,R}$ is the equivalent dose in tissue T and w_R is the radiation weighting factor

The SI unit of dose is the Sievert, Sv (1 Sv = 1 J kg-1, the old unit is the rem, 1 Sv = 100 rem).
This is the equivalent dose arising from an absorbed dose of 1 Gy

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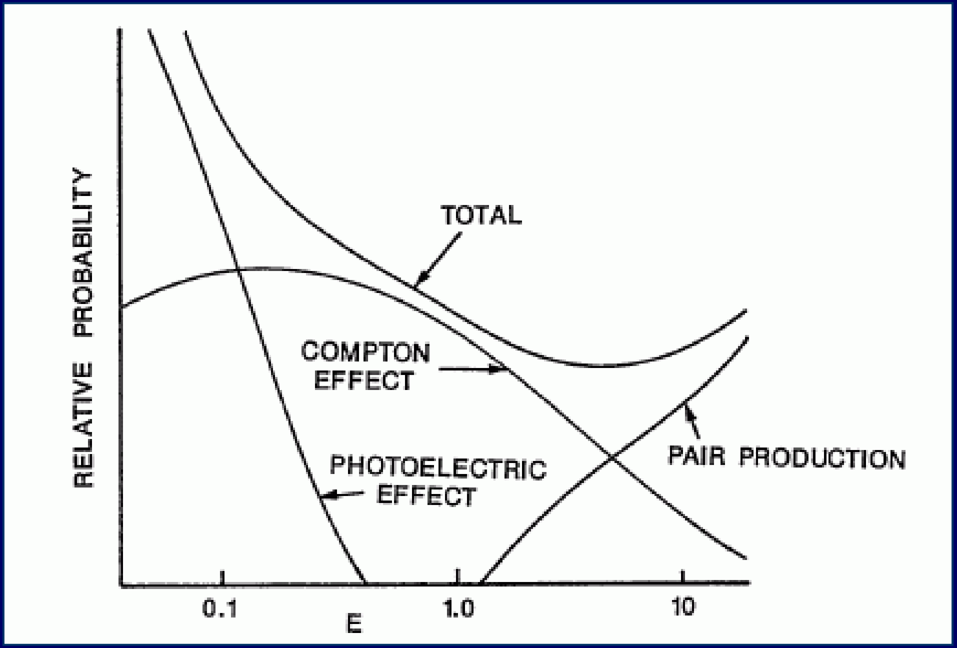
Attenuation of Gamma Radiation

The attenuation coefficient discussed above is a measure of how photons are removed from the beam under conditions of good geometry. Attenuation is a result of three basic processes: the photoelectric effect (pe), Compton scattering (cs), and pair production (pp) and the total attenuation coefficient is a sum of the attenuation coefficients for these processes.

$$\mu = \mu_{pe} + \mu_{cs} + \mu_{pp}$$

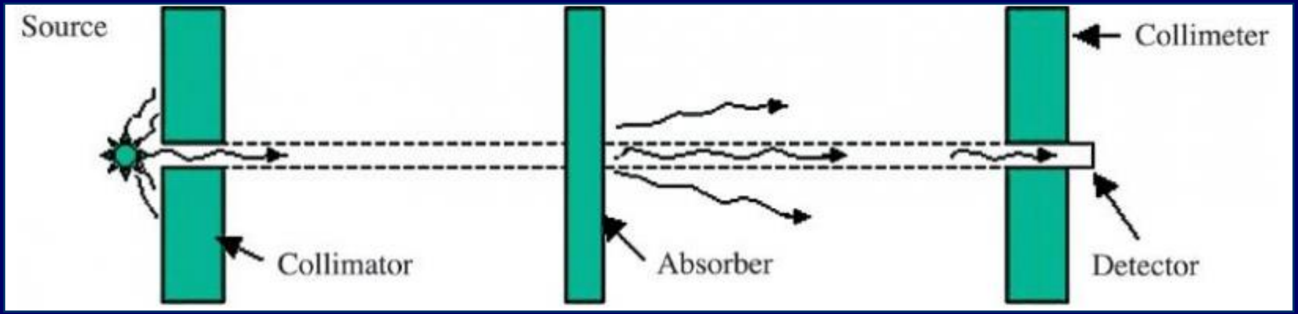
The total attenuation coefficient μ given above is the fraction of the energy of the beam that is removed per unit distance in the medium. The energy absorbed in the medium is determined by the energy absorption coefficient μ_{en}. The difference between μ and μ_{en} results from the fact that energy may be lost from the medium through Compton scattering and by annihilation radiation.

- *For dose calculations in tissue for example, the energy absorption coefficient μ_{en} must be used.*
- *For shielding calculations, the attenuation coefficient should be used.*



Attenuation of Gamma Radiation

Gamma radiation cannot be completely absorbed, but only reduced in intensity, when passing through matter. If mono-energetic gamma radiation attenuation measurements are made under conditions of good geometry, i.e. with a well-collimated, narrow beam of radiation, a straight-line relationship between the logarithm of the intensity versus the thickness d of the shield is obtained.



$$\frac{I}{I_0} = e^{-\mu d}$$

$$I = I_0 \cdot e^{-(\mu_t/\rho)\cdot(\rho d)}$$

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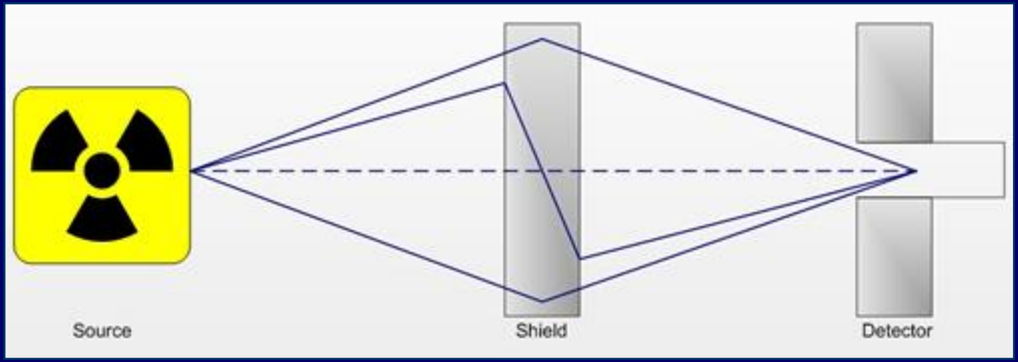
However, under conditions of poor geometry, i.e. for a broad beam or for a very thick shield, the above relation underestimates the required shield thickness. It assumes that every photon that interacts with the shield will be removed from the beam and thus will not be available for counting in the detector. Under conditions of poor geometry, as shown in Figure, this assumption is not valid; a significant number of photons may be scattered by the shield into the detector, or photons that had been scattered out of the beam may be scattered back in after a second collision.



Gamma radiation attenuation under conditions of broad beam geometry showing the effect of photons scattered into the detector

The shield thickness for conditions of poor geometry may be estimated by modification of the basic attenuation relation given above through the use of a build-up factor B, i.e.

$$I = B \cdot I_0 \cdot e^{-(\mu_t/\rho)\cdot(\rho d)}$$

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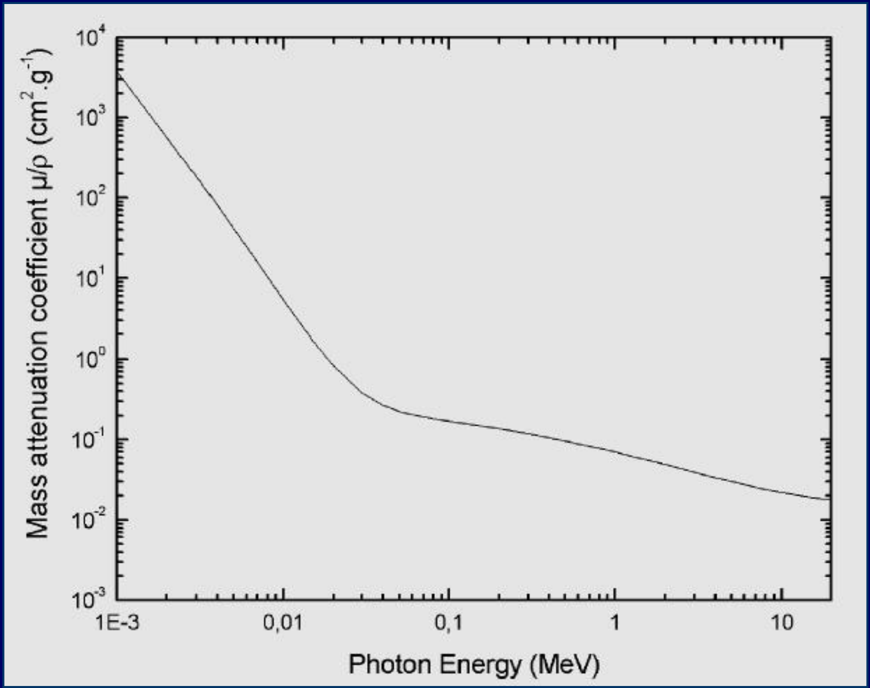
Calculation of the Equivalent Dose Rate

$$\frac{dH}{dt}(Sv/h) = (5.77 \cdot 10^{-4}) \cdot A/(4\pi R^2) \cdot \sum_i E_i(keV) \cdot P_i \cdot B_i \cdot e^{-(\mu_l/\rho)_i^{shield} \cdot (\rho d)} (\mu_l/\rho)_i^{tis}$$

$$\frac{dH}{dt}(Sv/h) = (5.77\cdot 10^{-4})\cdot A/(4\pi R^2)\cdot \sum_i E_i(keV)\cdot P_i\cdot B_i\cdot e^{-(\mu_l/\rho)_i^{shield}\cdot(\rho d)}(\mu_l/\rho)_i^{tis}$$

Absorption in Tissue

The dependence of $(\mu/\rho)_{tis}$ on energy is shown in Fig. 1. This data has been taken from the NIST database. In the calculations, a linear interpolation is carried out (actually the linear interpolation is carried out on the log (mass-absorption coefficient) vs. log(energy) plot). For energies lower than the minimum energy (0.001 MeV), an extrapolation is performed.



Mass absorption coefficient for tissue

Energy (MeV)	$(\mu/\rho)^{tis}$ (cm^2 g^{-1})	Energy (MeV)	$(\mu/\rho)^{tis}$ (cm^2 g^{-1})	Energy (MeV)	$(\mu/\rho)^{tis}$ (cm^2 g^{-1})
1.00E–03	3.70E+03	8.00E–03	9.94E+00	6.00E–01	3.25E–02
1.04E–03	3.38E+03	1.00E–02	4.99E+00	8.00E–01	3.18E–02
1.07E–03	3.08E+03	1.50E–02	1.40E+00	1.00E+00	3.07E–02
1.50E–03	1.25E+03	2.00E–02	5.66E–01	1.25E+00	2.94E–02
2.00E–03	5.58E+02	3.00E–02	1.62E–01	1.50E+00	2.81E–02
2.15E–03	4.57E+02	4.00E–02	7.22E–02	2.00E+00	2.58E–02
2.30E–03	3.78E+02	5.00E–02	4.36E–02	3.00E+00	2.26E–02
2.47E–03	3.09E+02	6.00E–02	3.26E–02	4.00E+00	2.05E–02
2.64E–03	2.59E+02	8.00E–02	2.62E–02	5.00E+00	1.90E–02
2.82E–03	2.14E+02	1.00E–01	2.55E–02	6.00E+00	1.79E–02
3.00E–03	1.82E+02	1.50E–01	2.75E–02	8.00E+00	1.64E–02
3.61E–03	1.06E+02	2.00E–01	2.94E–02	1.00E+01	1.55E–02
4.00E–03	8.03E+01	3.00E–01	3.16E–02	1.50E+01	1.42E–02
5.00E–03	4.14E+01	4.00E–01	3.25E–02	2.00E+01	1.36E–02
6.00E–03	2.39E+01	5.00E–01	3.27E–02		

Table of mass absorption coefficients for tissue

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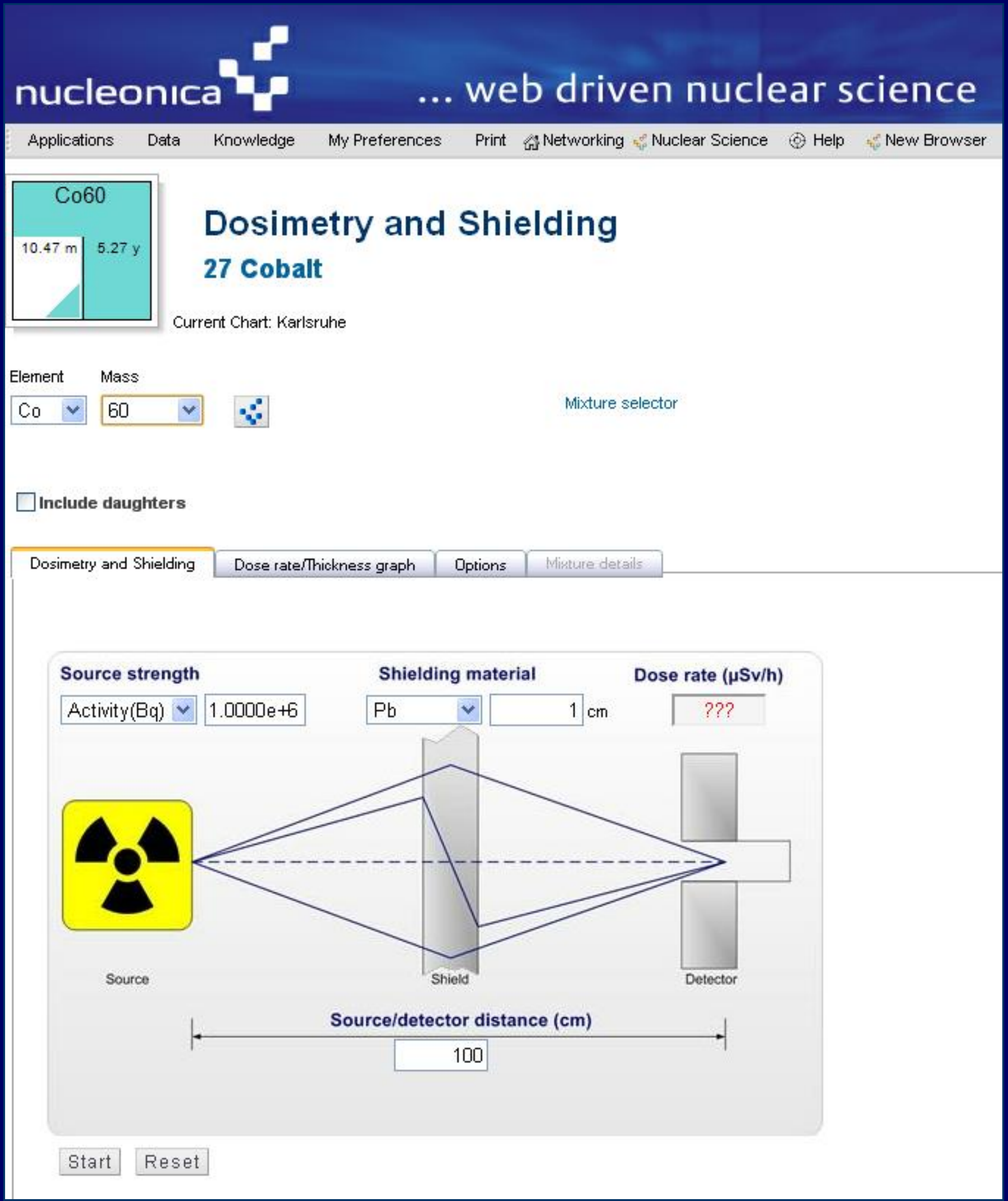
Nucleonica's
Dosimetry & Shielding Module

The Dosimetry and Shielding in Nucleonica allows the user to calculate gamma dose rates from point sources of single nuclides and nuclide mixtures. The user interface is shown in figure.

The main tab allows the user to select the nuclide source strength, source / detector distance, shield material and material thickness.



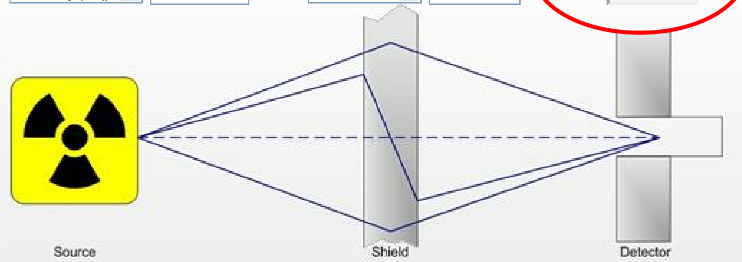
Results for 1MBq Co-60 with 1cm Pb shielding

Dosimetry and Shielding | Dose rate/Thickness graph | Options | Mixture details

Source strength: Activity(Bq) 1.0000e+6

Shielding material: Pb 1 cm

Dose rate (μSv/h): 2.67E-01



Source/detector distance (cm): 100

Start | Reset

Summary table…

Half-Value Shield Thickness(cm)	2.02E+00
Tenth-Value Shield Thickness(cm)	5.03E+00
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	3.37E-01
Tissue Gamma Dose Rate (μSv/h)	**2.67E-01**
Exposure Rate (μGy/h)	2.48E-01
Effective Build-up factor	1.55E+00
Effective Number of Mean Free Paths (μ·d)	6.70E-01

half- and tenth-value thicknesses of shield material and the specific gamma dose rate constant.

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Number of lines (γ):	6	ΣE.P.(γ):	2.50E+06
Number of lines (X):	4	ΣE.P.(X):	8.35E-01
Number of lines (γ+X):	10	ΣE.P.(total):	2.50E+06

Subsidiary quantities used in the calculations, such as the absorption coefficient, number of mean free path in the shield material, and the build-up factor for each energy line are given.

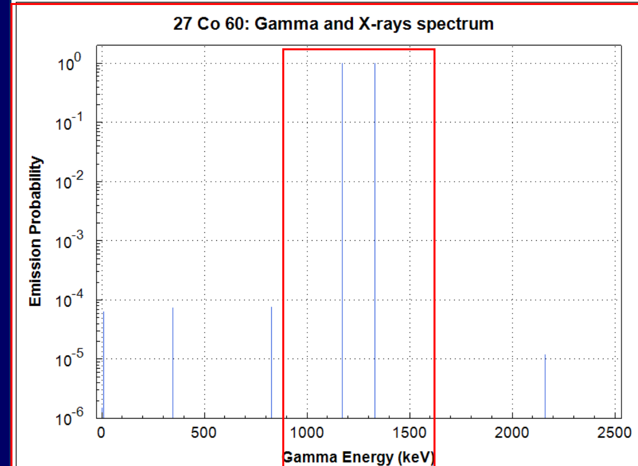
Show details…

Show radiation details

Nuclide	Gamma Energy (keV)	Emission Probability P (per disintegration)	Mass Attenuation Coefficient (shielding)(cm²/g)	Number of Mean Free Paths (μ·d)	Build-up Factor	Mass Absorption Coefficient (tissue)(cm²/g)	Tissue γ Dose Rate(μSv/h)	γ Exposure Rate(μGy/h)
27 Co 60	1332.49	1	0.0564	0.64	1.53E+00	0.0289	0.143	0.131
27 Co 60	1173.23	0.999	0.062	0.704	1.57E+00	0.0298	0.125	0.117
27 Co 60	826.1	7.6E-05	0.0859	0.975	1.69E+00	0.0316	5.83E-06	5.31E-06
27 Co 60	2158.57	1.2E-05	0.0454	[illegible]	[illegible]	[illegible]	2.66E-06	2.48E-06
27 Co 60	347.14	7.5E-05	0.305	[illegible]	[illegible]	[illegible]	2.18E-07	1.95E-07
27 Co 60	2505.69	2E-08	0.0439	[illegible]	[illegible]	[illegible]	4.97E-09	4.83E-09
27 Co 60	7.47815	6.44E-05	271	[illegible]	[illegible]	[illegible]	0	0
27 Co 60	7.46089	3.27E-05	272	3090	1	12.3	0	0
27 Co 60	8.26	1.31E-05	211	2400	1	9.01	0	0
27 Co 60	0.85	1.49E-06	7160	81200	1	5380	0	0

A list of all energy lines and emission probabilities used in the calculation are given

Gamma spectrum…



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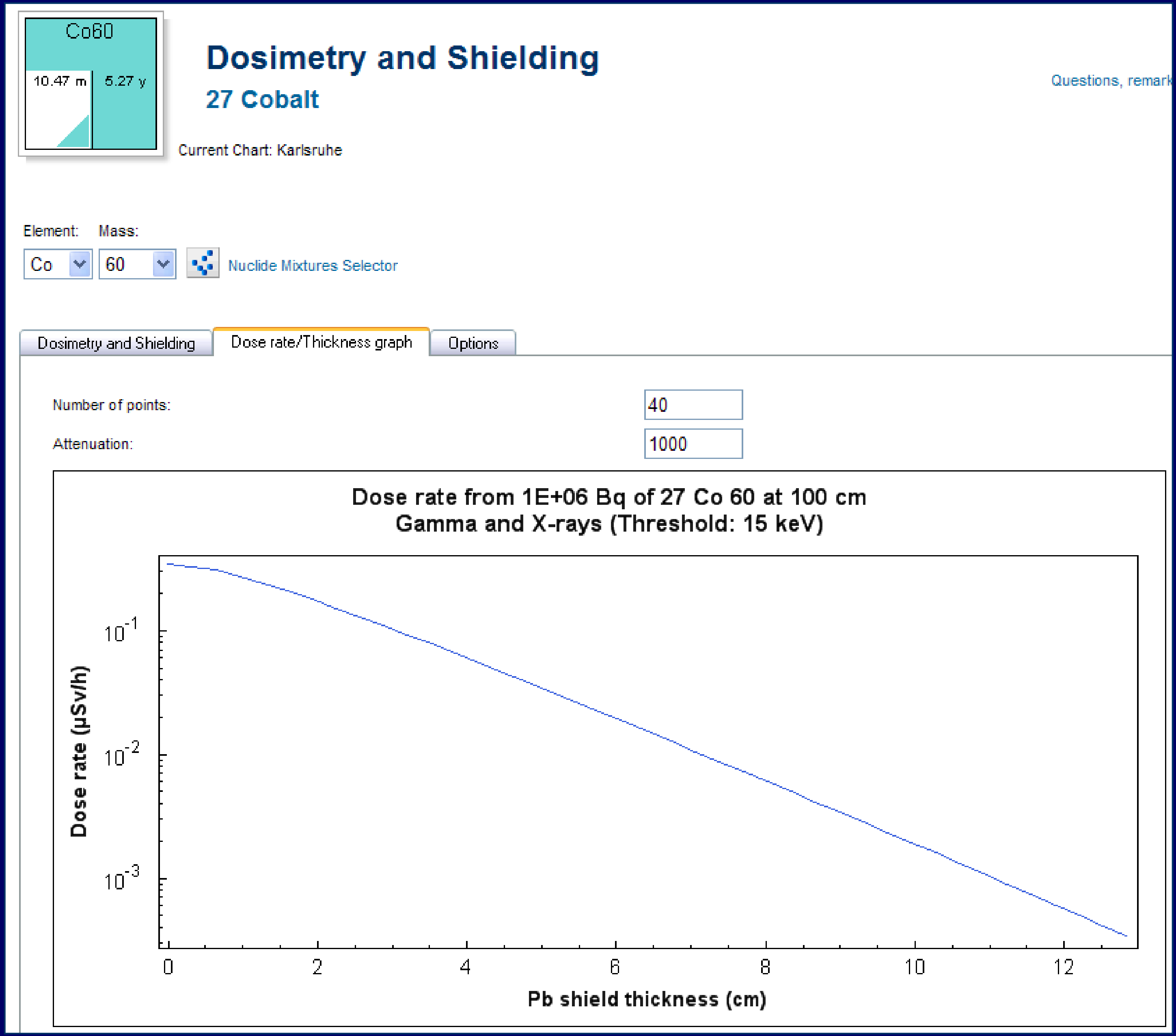
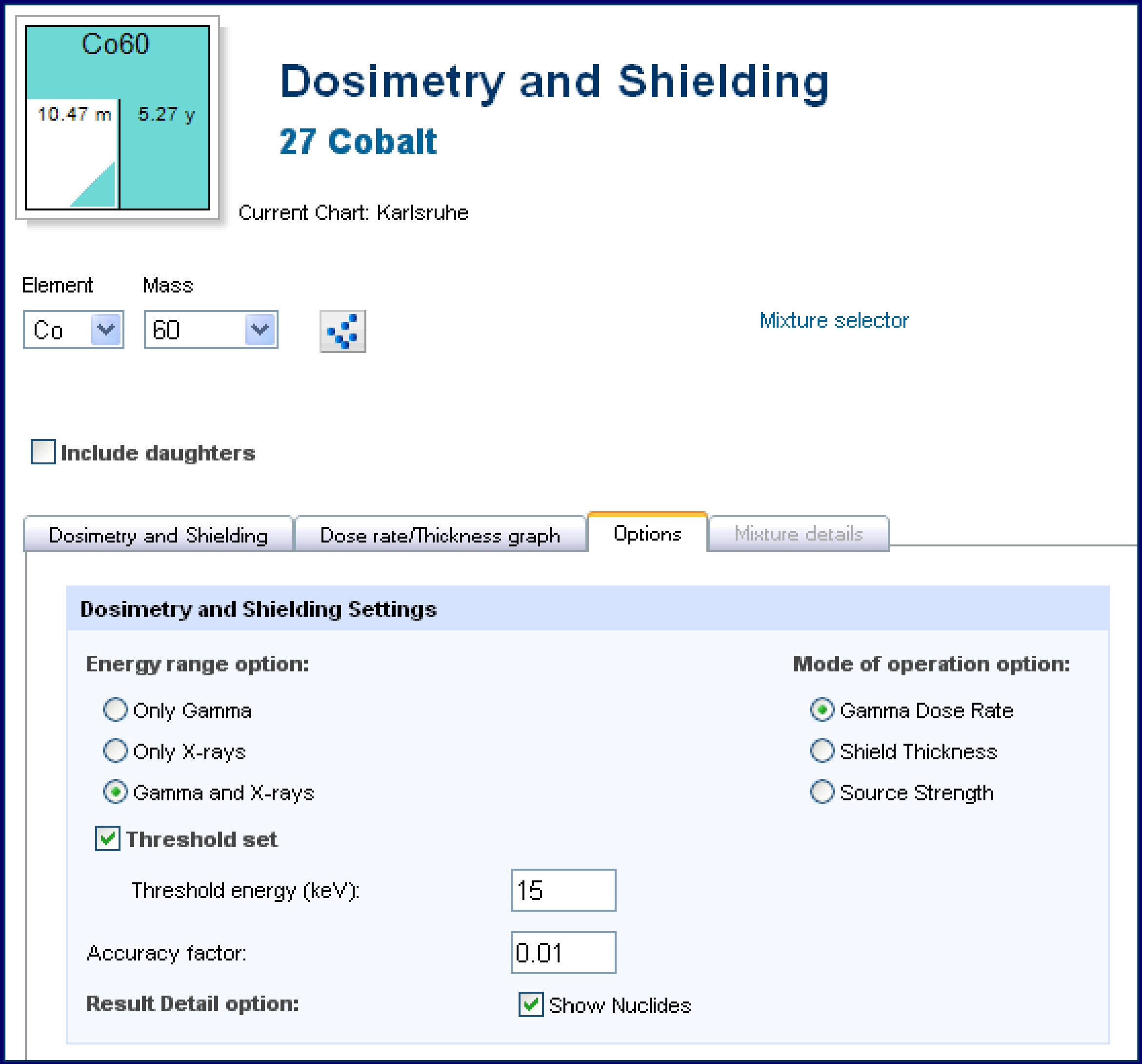
Dose Rate / Thickness Tab



Options Tab:

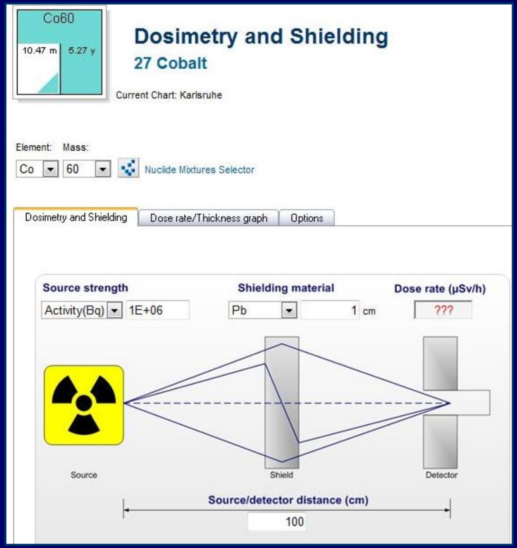
In the Energy range option, the user can choose to include only gammas, X-rays, or both in the calculation. In addition the user can set the minimum (threshold) energy of gamma and X-rays to be included in the calculation. The default value is 15 keV – photons with lower energy are absorbed by the outer layers of human tissue.

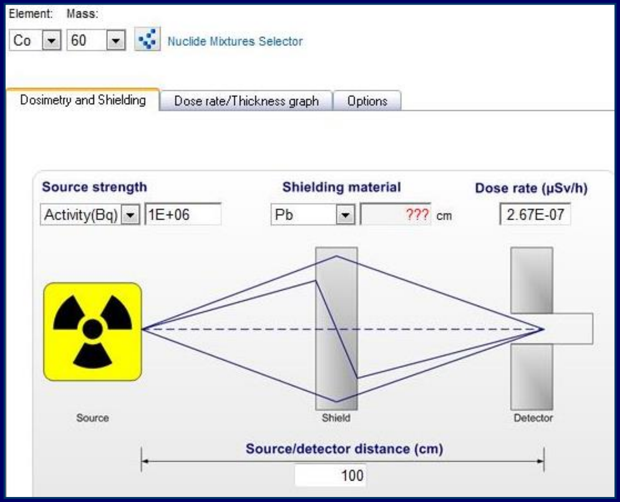


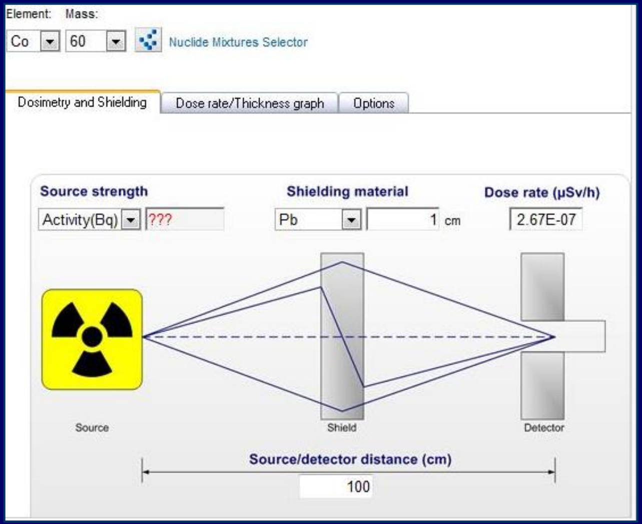
- Calculation of the dose rate for a given shield material and thickness.

- Calculation of the thickness of shield material required to obtain a given dose rate

- Obtain the source strength when the dose rate, shield material and thickness are known

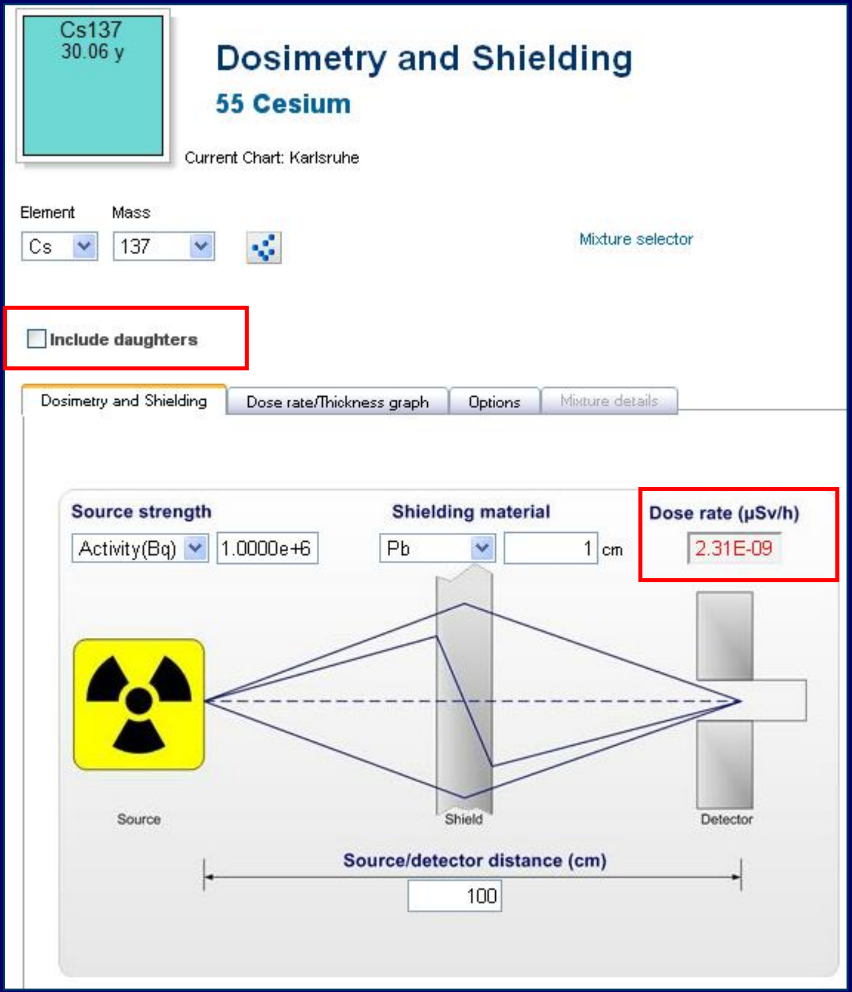


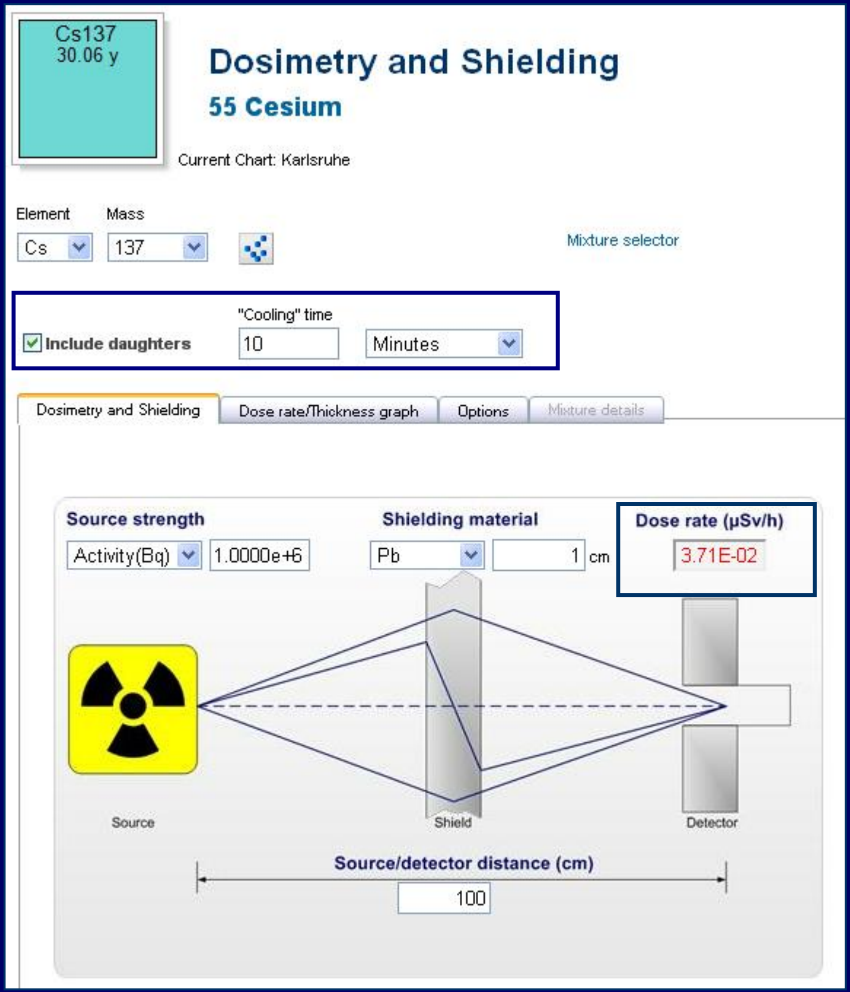




The importance of including daughters:

example: Cs137





Ba137m has a half-life of 2.55 min. Even after 10 mins, the Ba137m is the main dose contributor!

Nuclide	Half-life	Activity (Bq)	Mass (g)	Tissue γ Dose Rate(μSv/h)	γ Exposure Rate(μGy/h)
55 Cs 137	30.1671 y	1.00E+06	3.11E-07	2.31E-09	1.99E-09
56 Ba 137	Stable	0	9.21E-14	0	0
56 Ba 137m	2.55 m	8.82E+05	4.43E-14	3.71E-02	3.40E-02
Total: 3		1.88E+06	3.11E-07	3.71E-02	3.40E-02

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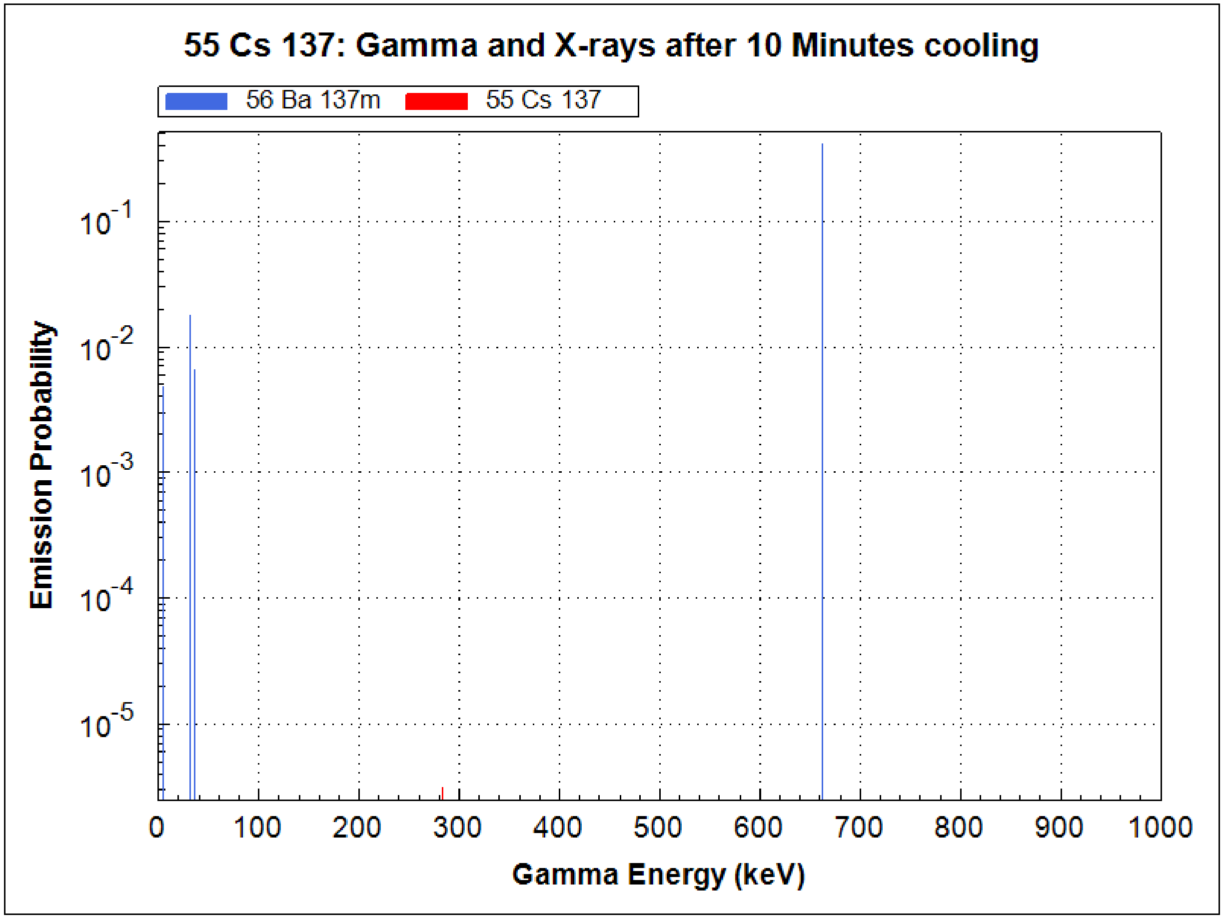
☐ Show radiation details



Cs137 lines are negligible….

Show radiation details

Nuclide	Gamma Energy	Emission Probability P	Mass Attenuation Coefficient	Number of Mean	Build-up	Mass Absorption Coefficient	Tissue γ Dose	γ Exposure
56 Ba 137m	661.657	0.422	0.111	1.26	1.69E+00	0.0323	0.0371	0.034
55 Cs 137	283.5	3.08E-06	0.457	5.19	1.76E+00	0.0313	2.31E-09	1.99E-09
56 Ba 137m	32.1936	0.0179	25.2	287	1.03E+00	0.133	0	0
56 Ba 137m	31.8171	0.00969	26	295	1.03E+00	0.137	0	0
56 Ba 137m	36.4	0.0065	18.4	209	1.04E+00	0.0941	0	0
56 Ba 137m	4.47	0.00488	956	10900	1	57.7	0	0

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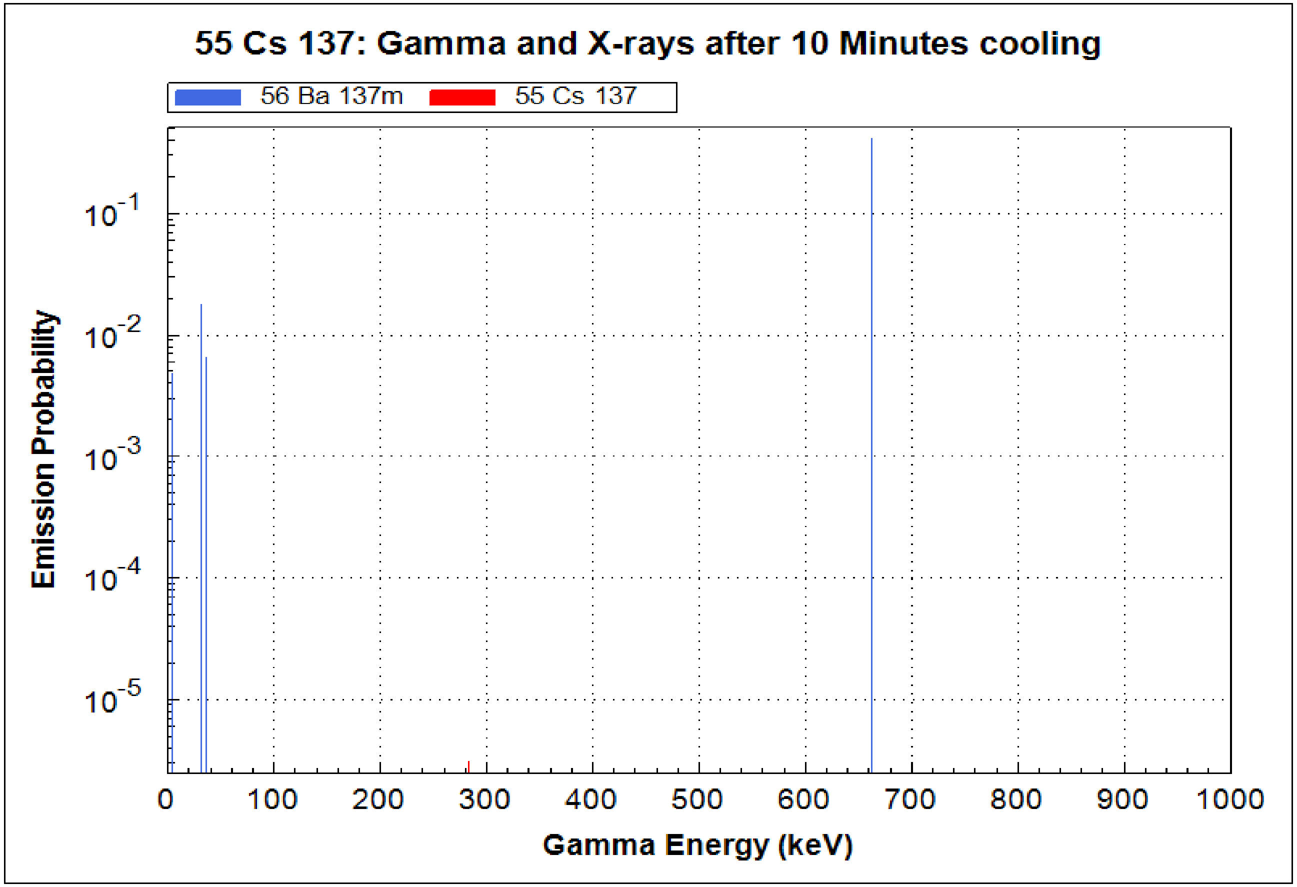

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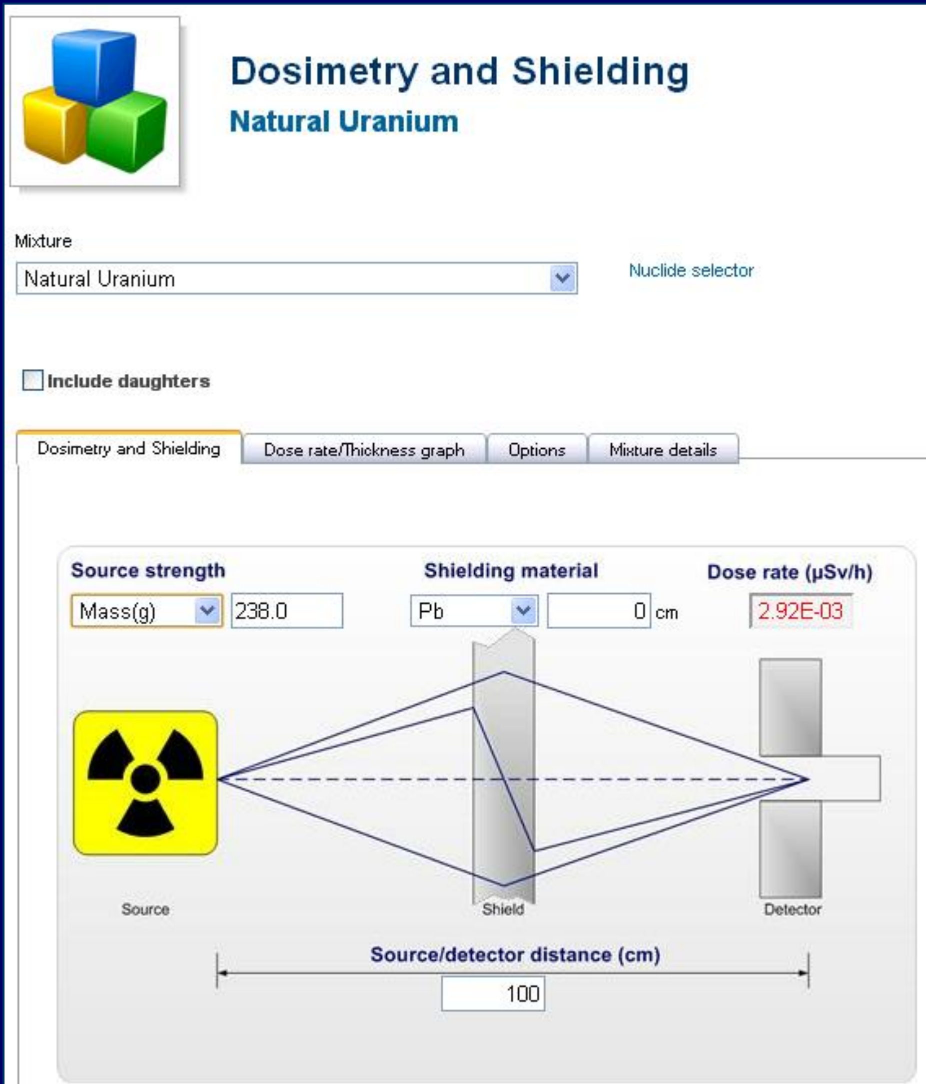
Mixtures: Example natural uranium at t=0



Nuclide	Half-life	Activity (Bq)	Mass (g)	Tissue γ Dose Rate(μSv/h)
92 U 234	245.5 ky	2.91E+06	1.26E-02	5.20E-05
92 U 235	704 My	1.35E+05	1.69E+00	2.84E-03
92 U 238	4.468 Gy	2.94E+06	2.36E+02	2.70E-05
Total: 3		5.98E+06	238	2.92E-03

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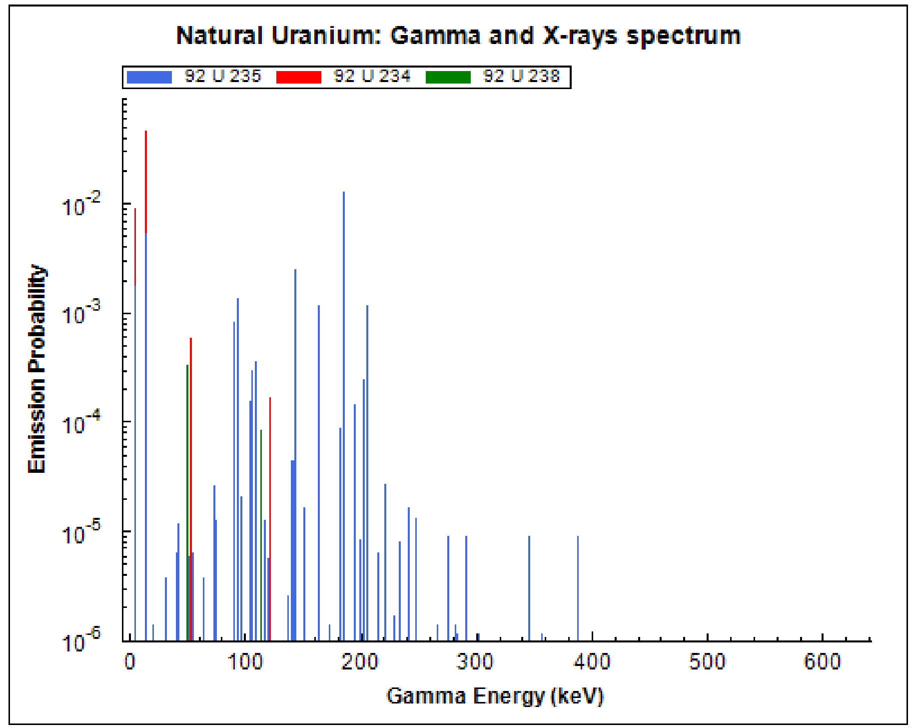
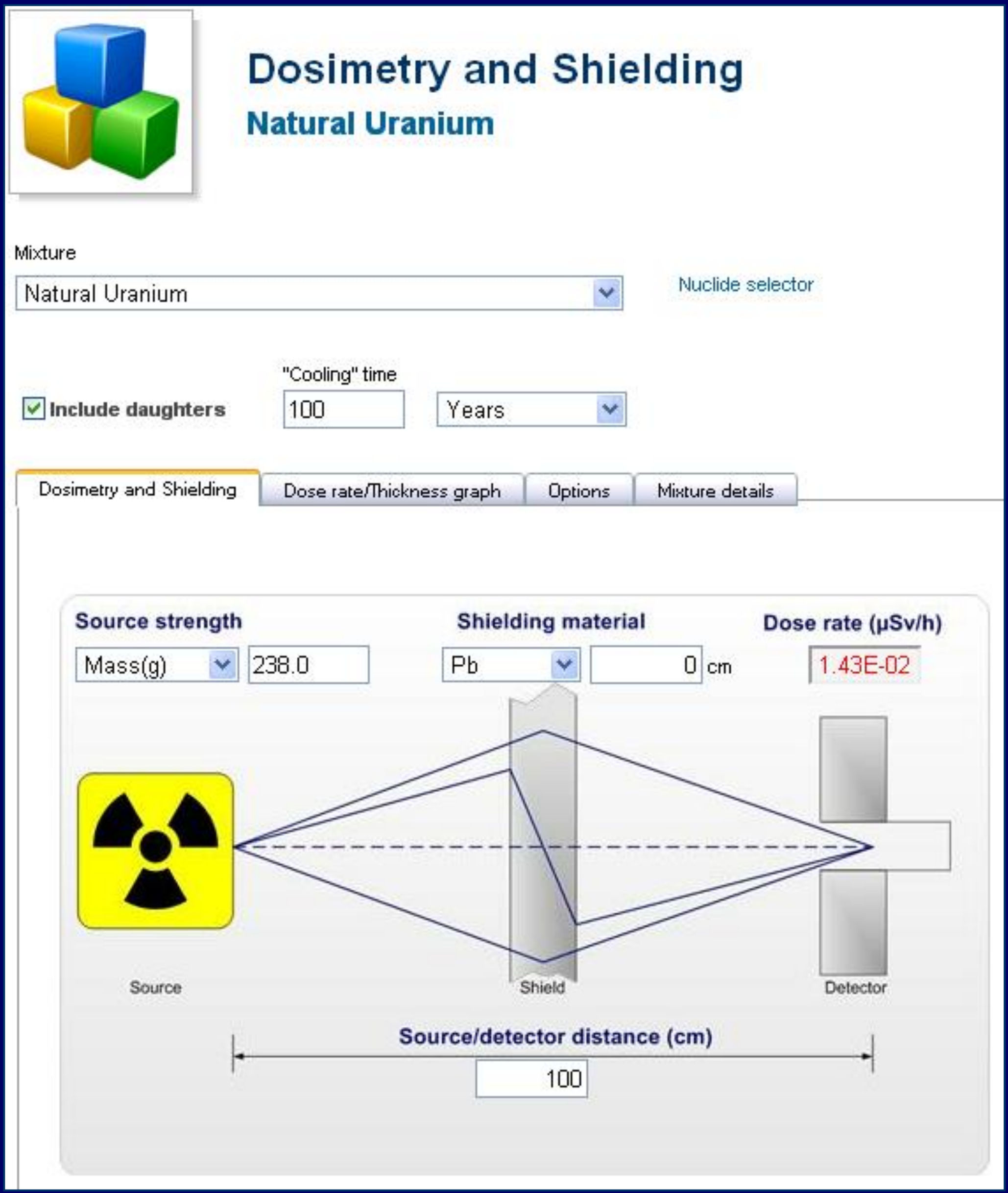


At t=0: no daughters

Mixtures: Example natural uranium at t=100y



82 Pb 206	Stable	0	9.41E-12	0
82 Pb 207	Stable	0	8.67E-11	0
82 Pb 210	22.20 y	3.17E+01	1.12E-11	1.47E-08
82 Pb 211	36.1 m	1.99E+02	2.18E-16	1.97E-06
82 Pb 214	26.8 m	5.69E+01	4.69E-17	1.94E-06
83 Bi 210	5.012 d	3.17E+01	6.90E-15	1.40E-12
83 Bi 211	2.14 m	1.99E+02	1.31E-17	1.39E-06
83 Bi 214	19.9 m	5.69E+01	3.48E-17	1.16E-05
84 Po 210	138.376 d	3.13E+01	1.88E-13	4.44E-11
84 Po 218	3.10 m	5.69E+01	5.53E-18	7.60E-11
86 Rn 219	3.96 s	1.99E+02	4.14E-19	1.60E-06
86 Rn 222	3.8235 d	5.69E+01	1.00E-14	3.32E-09
87 Fr 223	22.00 m	2.76E+00	1.93E-18	2.48E-08
88 Ra 223	11.43 d	1.99E+02	1.05E-13	3.49E-06
88 Ra 226	1.600 ky	5.70E+01	1.56E-09	5.37E-08
89 Ac 227	21.772 y	2.00E+02	7.47E-11	7.23E-09
90 Th 227	18.68 d	1.97E+02	1.73E-13	3.23E-06
90 Th 230	75.38 ky	2.67E+03	3.50E-06	1.36E-07
90 Th 231	25.52 h	1.35E+05	6.88E-12	7.95E-04
90 Th 234	24.10 d	2.94E+06	3.43E-09	2.83E-03
91 Pa 231	32.76 ky	2.86E+02	1.64E-07	2.21E-06
91 Pa 234	6.70 h	4.41E+03	6.03E-14	8.83E-04
91 Pa 234m	1.17 m	2.94E+06	1.16E-13	6.86E-03
92 U 234	245.5 ky	2.91E+06	1.26E-02	5.20E-05
92 U 235	704 My	1.35E+05	1.69E+00	2.84E-03
92 U 238	4.468 Gy	2.94E+06	2.36E+02	2.70E-05
Total: 28		1.20E+07	238	1.43E-02

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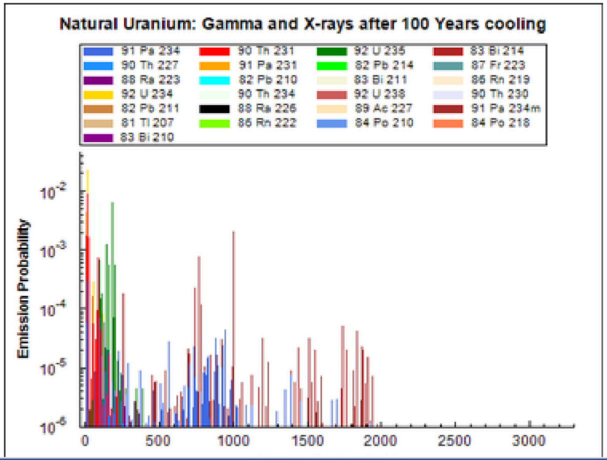
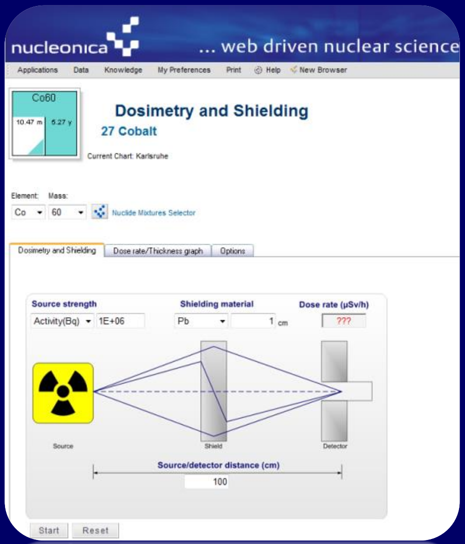


Shielding of Ionising Radiation

with the Dosimetry & Shielding Module

J. Magill



Overview…

Biological Effects of Ionising Radiation

- Absorber dose, Quality or Weighting Factor, Equivalent Dose

Attenuation of Gamma Radiation

- Calculation of the energy absorption, calculation of the equivalent dose rate, absorption in tissue, attenuation in shield materials, build-up factors

Nucleonica´s Dosimetry & Shielding Module

Hands on Exercises: Dosimetry & Shielding

1. What is the gamma dose rate from a 100 MBq source of Co-60 at 2m distance? (8.4 µSv/h)

2. A ^{60}Co gamma ray irradiation containing a 2TBq source is directed at a 30 cm thick concrete wall. The wall is situated at 7.5 m from the source. What the exposure rate behind the wall? (1.08 mGy/h)

3. Regulation impose an exposure rate outside the room of 7.5 µSv/h max. What thickness of wall would we then need? (75 cm)

4. We want to restrict the exposure rate inside the room (@1m from the irradiator) to 10 µSv/h using lead. Calculate the required thickness. (20 cm)

5. ^{99m}Tc is used in radioactive isotope medical tests, for example as a radioactive tracer that medical equipment can detect in the body. It is well suited to the role because it emits readily detectable 140 keV gamma rays, and it has a short half-life of 6.01 hours (meaning it has almost completely decayed to ^{99}Tc in 24 hours). A patient is injected 30 mCi of ^{99m}Tc. He is considered as an unshielded source during the time there is radioactivity in his body. Thus the staff is exposed to radiation. What is the equivalent dose rate that a staff member can be exposed to? (medium is tissue, 1 cm thick @1 m distance) (16.5 µSv/h)

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6. What is the gamma dose rate from 1 MBq freshly separated pure Cs-137 at 1m? (2.36E-7 µSv/h)

- Why is this so different to the ambient dose rate h_{10} =9.2E-2 µSv/h? (daughter Ba137m has not been considered)
- Redo the calculation for Cs-137 and include the daughters. What is now the gamma dose rate at 1m? (8.46E-2 µSv/h)

7. In question 6, the main gamma dose rate contribution arises from the Ba137m daughter of Cs-137. We are interested in comparing the gamma dose to the beta dose rate from Cs137:

- The beta particle energy from the decay of Cs-137 is 514 keV. Use the Range & Stopping Power module to calculate the range of this beta particle in tissue? (1.98 mm)

- Use the Virtual Cloud Chamber to show that 2 mm tissue is sufficient to block all beta particles (try using 1 mm, 1.5 mm, 2 mm). Use the following settings:
  Medium = Vacuum, Shield = Soft Tissue (ICRP), Shield thickness = 2 mm, Particle: electrons, Energy = 514 keV, No. particles = 100, Source diameter = 0 (point source), Magnetic field = 0.01 tesla, Source to shield distance = 10 cm, Source to detector = 20 cm

- Compare the h_{10} and h_{07} values. What do these quantities indicate?
  [h_{10}=9.2E-2 µSv/h (mainly gamma dose rate), h_{07} = 20 µSv/h (mainly ß dose rate)]